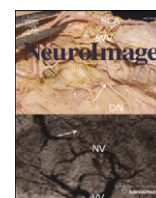




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MEG-compatible pneumatic stimulator to elicit passive finger and toe movements

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ABSTRACT

Magnetoencephalographic (MEG) signals recorded from the primary sensorimotor (SM1) cortex are coherent with kinematics of both active and passive finger movements. The coherence mainly reflects movement-related proprioceptive afference to the cortex. Here we describe a novel MEG-compatible stimulator to generate computer-controlled passive finger and toe movements that can be used as stimuli in functional brain-imaging experiments.

The movements are produced by pneumatic artificial muscle (PAM), elastic actuator that shortens with increasing air pressure. To test the applicability of the stimulator to functional brain-imaging, 4-min trains of passive repetitive 5-mm flexion-extension movements of the right and left index finger and the right hallux were produced at 3 Hz while the subject's brain activity was measured with whole-scalp MEG and finger or toe kinematics with an accelerometer. In all ten subjects studied, statistically significant coherence (up to 0.78) occurred between the accelerometer and MEG signals at the movement frequency or its first harmonic. Sources of coherent activity were in the contralateral hand or foot SM1 cortices. Movement-evoked fields elicited with intermittent movements of the right index finger (once every 3.2–4.0 s; mean \pm SD peak response latency 88 ± 25 ms) were co-located with the respective coherent sources.

We further moved the right index finger at 3, 6, and 12 Hz (movement ranges 5, 3, and 2 mm, respectively), and analyzed the first 1, 2, and 4-min epochs of data. One minute of data was sufficient to locate the left hand area of the SM1 cortex at all movement frequencies. Sound-induced spurious coherence was reliably ruled out in a control experiment.

Our novel movement stimulator thus provides a robust and reliable tool to track proprioceptive afference to the cortex and to locate the SM1 cortex.

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Introduction

We have recently demonstrated corticokinematic coherence (CKC) as a method to identify the human primary sensorimotor (SM1) cortex (Bourguignon et al., 2011, 2013). CKC quantifies the coupling between cortical activity, measured by means of magnetoencephalography (MEG), and hand kinematics (e.g. acceleration) during repetitive rhythmic voluntary (Bourguignon et al., 2011; Jerbi et al., 2007) and passive movements (Piitulainen et al., 2013a). CKC peaks at the movement frequency and its first harmonic, and it can be measured using various peripheral movement-related signals and motor tasks (Piitulainen et al., 2013b). Our previous research shows that CKC reflects proprioceptive input to the SM1 cortex (Piitulainen et al., 2013a) with an apparent

latency of 50–100 ms (Bourguignon et al., 2014) that corresponds to the timing of the strongest deflection of the cortical movement-evoked field (Cheyne et al., 1997). It is thus likely that the cortical generators of CKC and movement-evoked-fields are closely related.

In previous MEG studies, passive movements have been generated either manually, i.e. by an investigator moving the subject's finger or hand inside the magnetically shielding room (Druschky et al., 2003; Muthukumaraswamy, 2010; Onishi et al., 2013; Piitulainen et al., 2013a; Woldag et al., 2003; Xiang et al., 1997a, 1997b) or by devices relying on a pneumatic cylinder-lever system (Alary et al., 2002; Lange et al., 2001). Pneumatic cylinders can evoke rapid intermittent passive movements, appropriate for example to measurements of passive-movement-evoked fields (pMEFs). However, they produce considerable acoustic noise that needs to be masked e.g. by playing music to the subject (Alary et al., 2002). DC-motor-based movement actuators have been used during electroencephalographic recordings (Desmedt and Ozaki, 1991; Mima et al., 1996; Ramos-Murguialday et al., 2012), but unfortunately those devices are not MEG-compatible.

Abbreviations: CKC, corticokinematic coherence; ISI, inter-stimulus interval; pMEF, passive-movement-evoked field; SM1, primary sensorimotor.

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To remediate some caveats of previously used passive-movement stimulators, we here introduce a novel stimulator to elicit both intermittent and continuous passive movements by pneumatic artificial muscles (PAMs) that shorten with increased air pressure and return by their elastic properties to the initial resting length. The stimulator is nonmagnetic and therefore both MEG- and fMRI-compatible.

We tested the applicability of the PAM stimulator to functional mapping of the SM1 cortex by eliciting repetitive flexion–extension movements of ten subjects' index fingers and halluces, and we also tested the effect of movement frequency and recording duration on signal quality to optimize the stimulation parameters.

Materials and methods

Subjects

We studied ten healthy subjects (mean age 30.3 yrs, range 26–45 yrs; 5 males, 5 females) who did not report any history of movement disorders or neuropsychiatric disease. According to Edinburgh handedness inventory (Oldfield, 1971), all subjects were right-handed (mean score 93.8, range 70–100 on the scale from –100 to 100). The study had prior approval by the ethics committee of the Aalto University. The subjects gave informed consent before participation, and they were compensated monetarily for the lost working hours and travel expenses.

PAM stimulator

Fig. 1 shows the custom-made non-magnetic PAM stimulator to generate passive finger and toe movements. A pneumatic system is embedded into a PVC-plastic frame designed to support the subject's hand or foot. An elastic PAM (DMSP-10-100 AM-CM, diameter 10 mm, length of the contracting part 100 mm; Festo AG & Co, Esslingen, Germany; http://www.festo.com/rep/en_corp/assets/pdf/info_501_en.pdf) was attached vertically to the lower plate of the frame, extending 30 mm above the upper plate where the subject's hand or foot was

resting. The PAM moved in vertical direction when its internal air pressure (1–4 bar) changed. The pressure was regulated by a solenoid valve (SY5220-6LOU-01F-Q, SMC Corporation, Tokyo, Japan) that was controlled by computer-generated trigger pulses. The solenoid valve was placed outside the magnetically shielded room (MSR) and a 3.5-m non-elastic tube (internal diameter 2.5 mm) conveyed the airflow to the PAM. The PAM was first shortened by increasing the air pressure (opening of the valve), thereby flexing the finger or toe, and then returned back to the initial position when the air pressure was released (closing of the valve).

Experimental protocol

During MEG recordings, the subjects were sitting with the stimulated hand or foot on the upper plate of the stimulator placed on the table or on the floor in front of them (Figs. 2a and b). The other hand was resting on the thigh and the moved index finger or hallux was taped to the aluminum end of the pneumatic muscle. Earplugs were used to minimize concomitant auditory noise that arose from the airflow within the pneumatic muscle. A white A3-sized paper sheet, taped vertically to the MEG gantry, prevented the subjects from seeing the moving finger or toe. Subjects were instructed to fixate on a black dot on the wall of the MSR, 2.8 m in front of the eyes, 11 deg to the left or right from the midline, depending on the side of the movement.

Subjects underwent five continuous and one intermittent movement conditions as well as one control condition, each lasting 4 min, in a randomized order. Continuous passive flexion–extension movements were generated for the right index finger (at 3 Hz, 6 Hz, and 12 Hz), for the left index finger (3 Hz), and for the right hallux (3 Hz). Intermittent right index-finger movements were generated with inter-movement intervals (ISIs) of 3.2–4.0 s (mean ~3.6 s). The PAM stimulator moved mainly the metacarpophalangeal joint of the index finger and the metatarsophalangeal joint of the hallux. The movement range was 5 mm for intermittent movements as well as for continuous movements at 3 Hz, 3 mm at 6 Hz, and 2 mm at 12 Hz; these differences were due to stimulator limitations. In a control condition, designed to

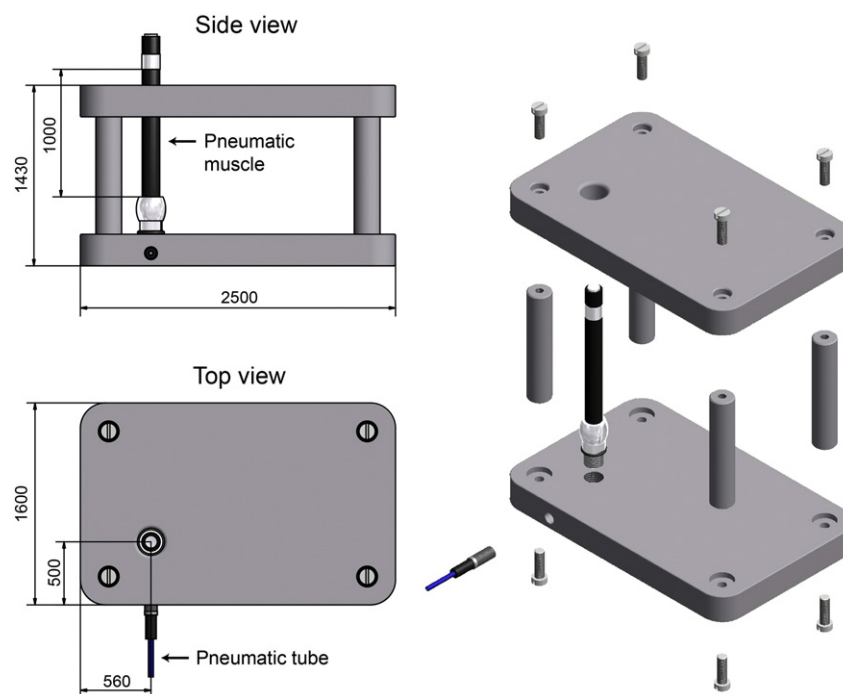


Fig. 1. Technical drawing of the pneumatic artificial muscle (PAM) stimulator used to generate passive movements. All materials and components are nonmagnetic. The dimensions are given in millimeters.

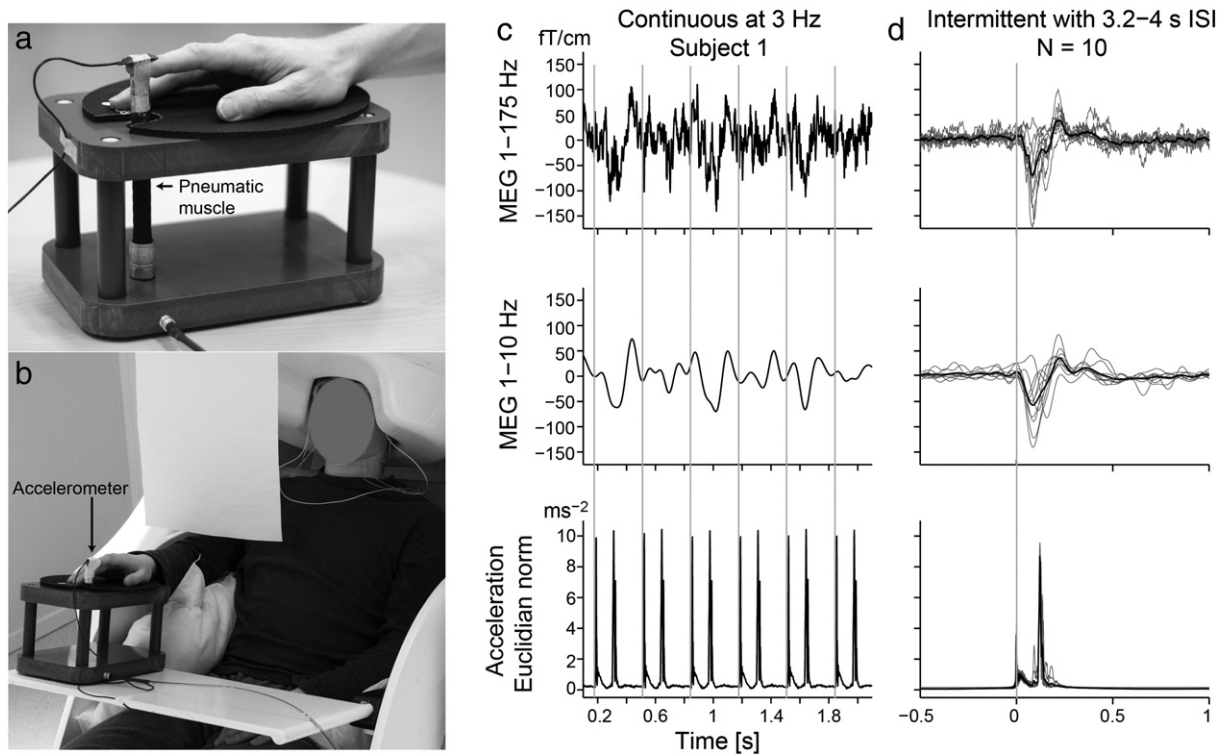


Fig. 2. Experimental setup and representative signals. (a and b) During MEG recordings, the subject's right-index finger was taped to the vertically moving pneumatic muscle, and an accelerometer was taped to the nail of the finger. (c) Representative MEG and accelerometer signals as a function of time when the right index finger of Subject 1 was moved at 3 Hz. (d) Individual subjects' passive movement-evoked-fields (pMEFs; grey thin traces) and their mean across the subjects (black thick trace) when the right index finger was intermittently moved once every 3.2–4 s. Rows from top to bottom in (c) and (d): MEG signals filtered at 1–175 Hz and 1–10 Hz (from the most responsive channel), and Euclidian norm of the three orthogonal acceleration signals. The grey vertical lines indicate the movement onsets.

unravel potential magnetic and auditory contamination, the subjects rested their both hands on the thighs, while the PAM stimulator was operating at 3 Hz, with the accelerometer attached to the moving pneumatic muscle.

Measurements

MEG

The measurements were carried out at the MEG Core, Aalto Neuro-Imaging, Aalto University. MEG signals were recorded in a MSR (Imedco AG, Hägendorf, Switzerland) with a 306-channel whole-scalp neuro-magnetometer (Elekta Neuromag™, Elekta Oy, Helsinki, Finland). The recording passband was 0.1–330 Hz and the signals were sampled at 1 kHz. The subject's head position inside the MEG helmet was continuously monitored by feeding current to five head-tracking coils located on the scalp; the locations of the coils with respect to anatomical fiducials were determined with an electromagnetic tracker (Fastrak, Polhemus, Colchester, VT, USA).

Acceleration and trigger signals

Index-finger and hallux accelerations were recorded with a 3-axis accelerometer (ADXL335 iMEMS Accelerometer, Analog Devices Inc., Norwood, MA, USA) attached to the nail of the moved finger or toe. Acceleration was low-pass filtered at 330 Hz and sampled at 1 kHz, time-locked to MEG signals. The digital trigger-signal, controlling the PAM stimulator, was recorded with other signals, and it was later used to determine the stability of the delay between the trigger and movement onsets. First the peak acceleration magnitude, i.e., the Euclidian norm of the three orthogonal accelerometer signals, was identified. Then, the movement onset was defined as the time when the acceleration reached 5% of its peak value.

MRI

3D-T1 magnetic resonance images (MRIs) were acquired with a whole-body General Electric Signa® VR 3.0 T MRI scanner (Signa VH/i, General Electric, Milwaukee, WI) or a 3 T MAGNETOM Skyra whole-body scanner (Siemens Healthcare, Erlangen, Germany) at AMI Centre, Aalto NeuroImaging, Aalto University.

Acoustic noise

To quantify the acoustic noise generated by the PAM stimulator, as well as the background noise in the MSR, we measured, with Sound Level Meter (Type 2250, Brüel & Kjær, Nærum, Denmark), the maximum A-weighted (from 20 Hz to 20 kHz) impulse sound pressure level (LAImax) during 30-s operation at the subjects' location (80 cm from the stimulator). Noise was measured separately for all movements used in this study.

Data processing

Preprocessing

Continuous MEG data were first preprocessed off-line using signal-space-separation (SSS) to suppress external interferences and to correct for head movements (Taulu et al., 2004). The MEG and acceleration signals were band-pass filtered offline at 1–175 Hz.

Stimulator parameters

Data of the intermittent movements (ISI 3.2–4 s) were used to quantify the temporal regularity of the passive movements by computing the coefficient of variation of the peak acceleration magnitude (i.e. Euclidian norm of the three orthogonal acceleration signals).

Coherence analysis

For frequency and coherence analyses, the continuous data were split into 2-s epochs with 1.6-s epoch overlap, leading to frequency resolution of 0.5 Hz (Bortel and Sovka, 2007). MEG epochs with magnetometer signals >3 pT or gradiometer signals >0.7 pT/cm were excluded to avoid contamination by eye movements and blinks, muscle activity, or external MEG artifacts. We then performed coherence analysis (Halliday et al., 1995)—yielding cross-, power- and coherence spectra, as well as cross-correlograms—between MEG signals and the Euclidian norm of the three orthogonal accelerometer signals. Before the coherence analysis, each epoch of acceleration was normalized by its Euclidian norm (Bourguignon et al., 2011).

To study the effect of movement frequency and recording duration on the CKC-based functional mapping, the coherence analysis was repeated using the first 1-, 2-, and 4-min of data from 3-, 6-, and 12-Hz right index-finger movements.

Cortical sources

Cross-correlograms were band-pass filtered at 1–20 Hz for continuous 3-Hz movements, at 2–40 Hz for 6-Hz movements, and at 4–80 Hz for 12-Hz movements. Source analysis was performed in time domain, on the spatial distribution of the filtered cross-correlogram, as previously done in CKC studies (Bourguignon et al., 2011, 2013; Piitulainen et al., 2013b). The passive-movement-evoked fields (pMEFs) elicited by intermittent movements, and obtained by averaging MEG activity with respect to movement onsets (as defined in ‘Measurements’), were filtered through 1–40 Hz, and the source analysis was performed on the spatial distribution of the main peak of the pMEF.

Individual MRIs were used to fit a spherical head model to the centroparietal brain region. Then, equivalent current dipoles (ECDs) were estimated within the spherical head model at the main peak of the filtered cross-correlogram (continuous movements) or pMEFs (intermittent movements), using a fixed selection of 60 sensors (40 gradiometers and 20 magnetometers) over the sensorimotor cortex contralateral to the movement. ECDs were visualized on the coregistered individual MRIs.

Spread of the cortical sources

In each subject, the dipole's centroid was first calculated as the mean of all ECD coordinates across the four right finger movement conditions (3, 6, and 12 Hz, and intermittent). Then, ECD coordinates relative to the centroid were subjected to a principal component analysis. The spread of the ECDs was then characterized by the standard deviation (SD) of their coordinates projected on the first principal axis (i.e. the direction of maximal variance), or equivalently by the first singular value divided by the square root of the number of ECDs used in the principal component analysis (Fischer et al., 2005). The same analysis was performed for 3-, 6-, and 12 Hz right-index movement conditions using the first 1-, 2-, and 4-min of data.

Statistical analysis

Statistical significance of coherence

The statistical significance of individual coherence levels (maximum value across a pre-selection of 40 gradiometers) was assessed under the hypothesis of linear independence of Fourier coefficients from epoch to epoch at each frequency of interest, taking into account the use of overlapping epochs (Halliday et al., 1995; Bourguignon et al., 2011). To correct for multiple comparisons, the alpha level was set to 0.05 / (Nf × Ns), Nf = 2 being the number of tested frequency bins (movement frequency and its first harmonic) and Ns = 40 the number of gradiometers included in the analysis.

Results

Fig. 2c illustrates MEG and acceleration signals of a representative subject (S1) during 3-Hz right index-finger movements. The PAM stimulator did not produce any artifact into the MEG signals, and thus the strong fluctuations at movement frequency, clearly visible in the wide-band (1–175 Hz) MEG signal, reflect the cortical activity related to proprioceptive afference. The acceleration signals contain two clear peaks during each movement cycle, reflecting the initiations of the flexion and extension. Fig. 2d shows averaged MEG and acceleration signals superimposed for all subjects during the intermittent movements. The mean ± SD delay (across ten subjects) between the trigger and movement onset was 36 ± 0.5 ms, and the mean peak acceleration magnitude was 8.7 ± 0.8 ms⁻². During intermittent movements, the coefficient of variation for the peak acceleration magnitude was only 0.015 ± 0.011 .

Acoustic noise

The maximum stimulator-related sound pressure level was 39.0 dB at 3 Hz, 35.7 dB at 6 Hz, 38.7 dB at 12 Hz, and 34.5 dB during the intermittent movements, thereby exceeding the background noise level (30.2 dB) in the MSR. Third-octave-band analysis indicated that most of the energy of the impulse-type stimulator noise was between 315 Hz and 6300 Hz. Five subjects reported that the earplugs blocked the movement-related sounds totally, while one subject heard occasionally a weak but distinguishable movement-related sound. However, the sound was not strong enough to elicit any detectable auditory-evoked fields even in this subject.

Coherence

Fig. 3 shows, superimposed for all subjects, the MEG–acceleration coherence spectra. Typically, the coherence was very strong (even 0.78 on a scale from 0 to 1), and it was statistically significant ($p < 0.05$) in all subjects and at all movement frequencies either at the movement frequency or its first harmonic. Possibly due to the very stable movement frequency, several clear harmonics occur beyond the first harmonics. Table 1 shows the mean ± SD coherence values at each movement frequency and its first harmonic. No significant coherence was observed during the control condition.

Cortical sources

Fig. 4 illustrates the spatial distribution of the MEG–acceleration cross-correlograms and the respective magnetic field patterns for one representative subject (S1). At the time of the main peak of the cross-correlograms, clear dipolar field patterns are centered on the left rolandic sensors (right index), right rolandic sensors (left index) or left interhemispheric sensors (right hallux) near the central sulcus. Similar patterns were observed in all subjects. The applied fixed selections of MEG sensors for right and left index finger and right hallux movements are also outlined. Note that the direction of the ECD is opposite during successive peaks of the cross-correlogram.

Fig. 5 shows the location of sources in Subject 1. The sources for finger and toe movements agree with the somatotopical order of the contralateral SM1 cortex. At group level, the spread of the ECD clusters (SD along the principal direction) for the sources of the four different right-index finger movements (continuous 3, 6, 12 Hz, and intermittent) was 3.0 ± 1.2 mm. Table 2 shows the goodness-of-fit values and the volumes of confidence for all ECDs.

Movement frequency and recording duration

Fig. 6 illustrates successive averages across 20-s epochs for the 3-, 6-, and 12-Hz movements. At 3 Hz, transient responses are visible, whereas at 12-Hz, steady-state responses emerge at a frequency double the movement frequency; the two response cycles within one movement cycle have slightly different amplitudes. The responses decreased in amplitude with increasing movement frequency. The decrease in

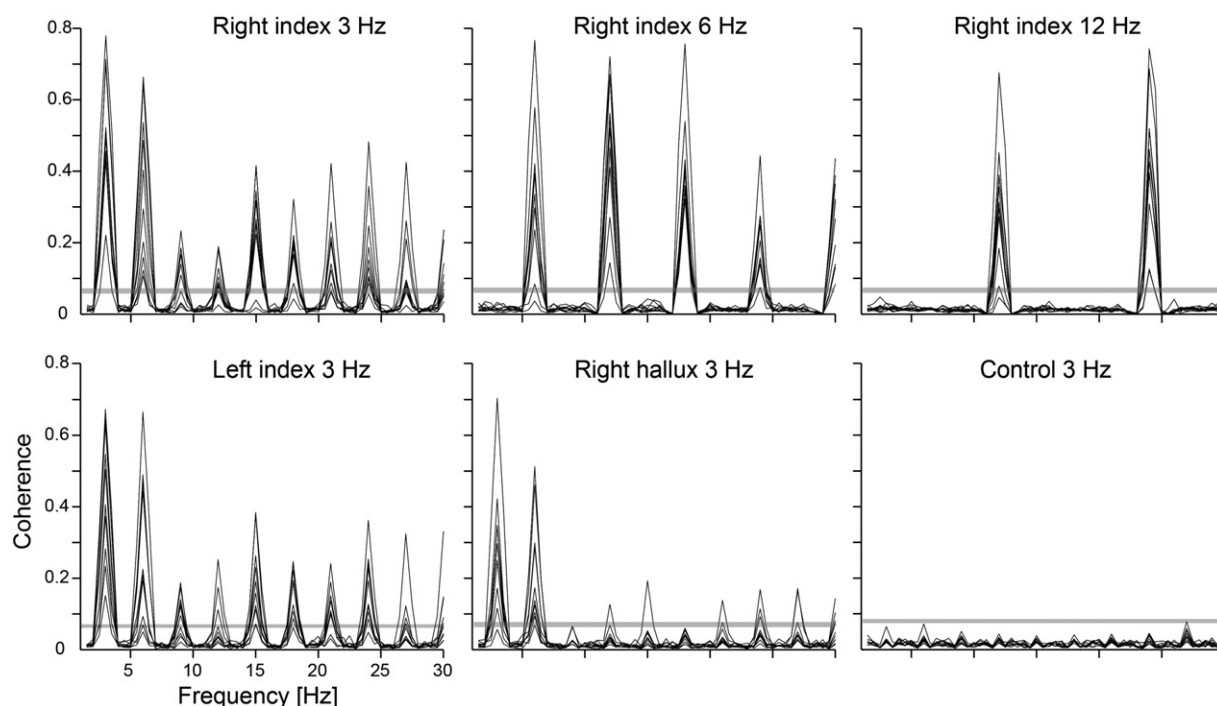


Fig. 3. Individual coherence spectra for the ten subjects in six experimental conditions. Maximum coherence is shown between the acceleration and respective pre-selected 40 gradiometers. In control condition, the accelerometer was attached to the moving pneumatic muscle while subjects rested their hands on lap. Gray horizontal lines show the threshold of statistical significance ($p < 0.05$).

amplitude compared with intermittent movements ($3.2\text{--}4$ s ISI; peak-response latency 88 ± 25 ms) was $61 \pm 6\%$ at 3 Hz, $62 \pm 10\%$ at 6 Hz, and $80 \pm 6\%$ at 12 Hz.

During the first 1-min or 2-min of right index-finger movements, the coherence remained statistically significant ($p < 0.05$) in all subjects and movement frequencies. Table 1 shows the mean \pm SD coherence values at movement frequency and its first harmonic estimated from the first 1-, 2-, and 4-min of data. The sources of coherent activity of the 3, 6, and 12 Hz movements were located close to each other in the hand area of the left SM1 cortex based on either the first 1-min, 2-min, or 4-min of the data. The spread of the ECD clusters was 2.8 ± 1.0 mm for 4-min, 3.3 ± 1.1 mm for 2-min and 3.6 ± 1.0 mm for 1-min of data. Table 3 shows the respective goodness-of-fit values and the confidence volumes for the ECDs.

Discussion

We introduced a novel passive-movement stimulator based on pneumatic artificial muscles (PAMs). The PAM stimulation led to a strong coherence between finger/toe kinematics and cortical MEG signals, in accordance with earlier findings where the experimenter moved the subject's finger (Piitulainen et al., 2013a). Sources of the

coherent activity corresponded to the hand or foot area in the SM1 cortex contralateral to the movement. Similar source locations were observed for the right index-finger movements at all frequencies (3, 6, and 12 Hz, and intermittent). Moving the finger continuously only for 1-min was sufficient to elicit reliable CKC that allowed the identification of the hand area in the SM1 cortex.

Benefits and limitations

The computer-controlled PAM stimulator did not produce any mechanical or electrical artifacts into the MEG signals, and it created only subtle acoustic noise. It can thus be used as a robust tool to provide a unique measure of proprioceptive afference to the cortex, and to locate the human SM1 cortex.

The PAM stimulator has some benefits with respect to movements elicited by an experimenter (Druschky et al., 2003; Muthukumaraswamy, 2010; Onishi et al., 2013; Piitulainen et al., 2013a; Woldag et al., 2003; Xiang et al., 1997a, 1997b) or by pneumatic-cylinder-based devices (Alary et al., 2002; Lange et al., 2001). Importantly, the timing of the movements can be freely varied and controlled with millisecond accuracy via a computer. Additionally, movements up to 20 Hz can be generated, even though at

Table 1
Group mean (\pm SD) coherence values between the index-finger or hallux acceleration and MEG for 4-, 2-, and 1-min epochs of signals. Individual coherence values were obtained as the maximum coherence across the 40 pre-selected gradiometer channels at the movement frequency and its first harmonic.

Condition	Movement frequency			First harmonic		
	4 min	2 min	1 min	4 min	2 min	1 min
Right hand 3 Hz	0.53 ± 0.17	0.55 ± 0.16	0.62 ± 0.14	0.36 ± 0.21	0.38 ± 0.22	0.48 ± 0.19
Right hand 6 Hz	0.35 ± 0.22	0.42 ± 0.22	0.47 ± 0.20	0.50 ± 0.18	0.55 ± 0.18	0.55 ± 0.16
Right hand 12 Hz	0.31 ± 0.19	0.37 ± 0.21	0.39 ± 0.20	0.43 ± 0.21	0.46 ± 0.21	0.49 ± 0.20
Left hand 3 Hz	0.45 ± 0.18	–	–	0.29 ± 0.21	–	–
Right hallux 3 Hz	0.30 ± 0.18	–	–	0.23 ± 0.16	–	–
Control	0.03 ± 0.01	–	–	0.03 ± 0.02	–	–

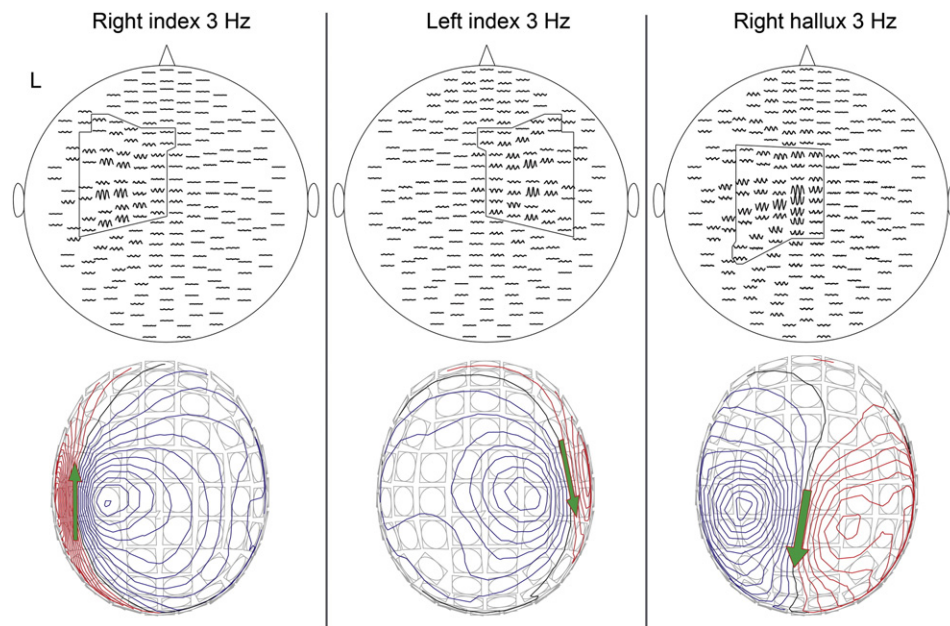


Fig. 4. Spatial distributions of cross-correlograms and corresponding magnetic field patterns superimposed on the MEG sensor array (only the pairs of orthogonal gradiometers are displayed) for Subject 1 during right index finger, left index finger, and right hallux movements at 3 Hz. The pre-selected subsets of sensors are outlined. Magnetic field patterns were obtained at the main peak of the cross-correlogram. The red isocontour lines indicate magnetic flux out of the skull and the blue lines flux into the skull. The arrows depict the surface projection of the ECDs; the current direction alternated during successive peaks of the steady-state response. L indicates left hemisphere.

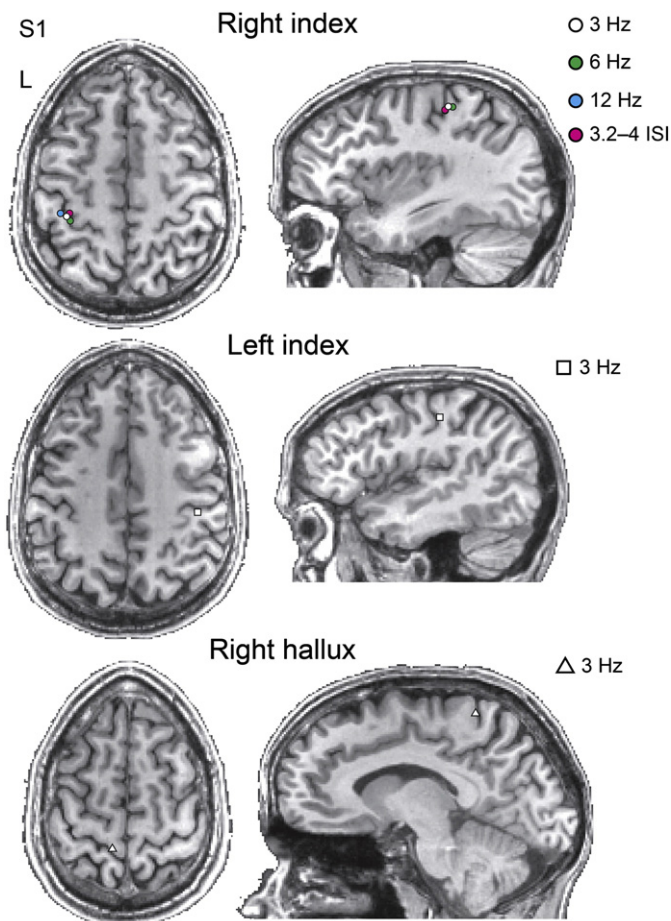


Fig. 5. The source locations superimposed on the MRI of Subject 1 in transverse (left) and sagittal (right) planes. For continuous movements at 3, 6, and 12 Hz, the sources were computed from the cross-correlograms between MEG and acceleration signals. For intermittent movement every 3.2–4 s, the sources were computed from passive movement-evoked-fields.

slightly decreased movement ranges due to incomplete release of the air pressure from the pneumatic muscle at high stimulation rates. The movement range also depends on the length of the pneumatic muscle, which can contract up to 25% of its resting length. The up to 5-mm movement range of our PAM stimulator was appropriate for the current purpose. However, significantly larger movement ranges can be achieved by modifying the design.

It is well known that the proprioceptors sensing the internal state of the musculoskeletal system are extremely sensitive. During vibration, for example, muscle spindles are activated by 5- μ m length changes of their parent muscle (Brown et al., 1967). Thus, movement amplitudes of a few millimeters are well sufficient to elicit reliable CKC and pMEFs. Mechanoreceptors of the skin were also likely activated during the PAM stimulation as e.g. Pacinian corpuscles are activated by 10-nm skin motions (Brisben et al., 1999). However, previous results indicate that cutaneous stimuli do not have significant effect on the strength of CKC during either active or passive index-finger movements (Piitulainen et al., 2013a).

The acceleration magnitude of the successive PAM-elicited movements was well reproducible both within and between individuals. The movement kinematics can be adjusted by changing the length (or diameter) of the PAM, or by varying the air pressure; higher pressure provides brisker movements. The delay between trigger onset and movement onset remained practically constant during the stimulation, varying only up to 1 ms between individuals. The high sta-

Table 2

The mean \pm SD goodness-of-fit (GoF) values and 95%-confidence volumes (CVs) of the sources based on the cross-correlograms and pMEFs in each movement condition, and for SEFs.

Condition	GoF (%)		CV (mm ³)	
	Mean \pm SD	Range	Mean \pm SD	Range
Right hand 3 Hz	95.4 \pm 3.3	89.7–98.3	29 \pm 27	2–90
Right hand 6 Hz	95.5 \pm 2.0	92.8–98.5	17 \pm 23	1–77
Right hand 12 Hz	95.1 \pm 1.9	92.0–98.8	106 \pm 122	6–364
Left hand 3 Hz	94.2 \pm 2.8	88.5–98.2	35 \pm 41	1–117
Right hallux 3 Hz	94.2 \pm 3.4	88.3–97.8	263 \pm 289	25–938
Right hand SEFs	93.7 \pm 6.7	78.8–99.2	83 \pm 144	3–453

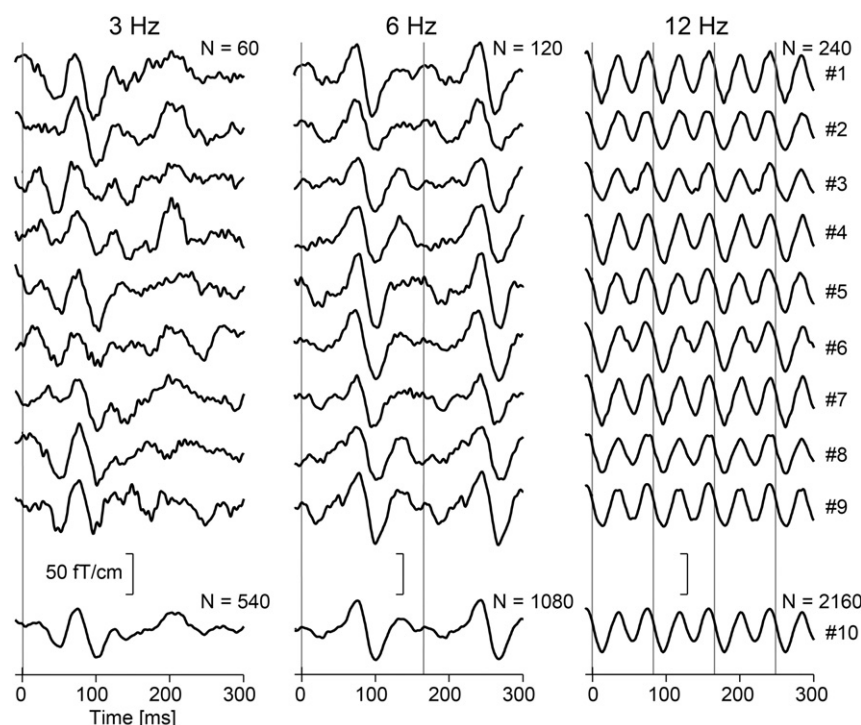


Fig. 6. Averaged MEG signals from Subject 1 during continuous right-index-finger movements at 3 Hz (left column), 6 Hz (middle), and 12 Hz (right). Labels #1–9 refer to averages within the 9 successive 20-s sections of data from 5 to 185 s, and #10 is the average across the whole 5–185-s period. The signals are from the rolandic MEG gradiometer showing the highest coherence with the acceleration. The grey vertical lines indicate movement onsets.

bility of the PAM stimulator is a desirable feature for future longitudinal studies of proprioceptive afference during e.g. stroke recovery or motor learning.

Electrical stimulation of peripheral nerves provides a simple approach to identify the hand area of the SM1 cortex in healthy (for a review, see e.g. Hari and Forss, 1999) and diseased individuals (Mäkelä et al., 2001). However, the PAM stimulator provides a specific means to activate the proprioceptive afferents.

Cortical sources

In all movement conditions and all subjects, the magnetic field patterns were adequately (>80% of field variance) explained by a single ECD in the contralateral SM1 cortex. The sources to right index-finger movements (including the pMEFs) clustered close to each other in the hand area of the left SM1 cortex, in accordance with the experimenter-elicited passive movements (Piitulainen et al., 2013a) and active-hand movements (Bourguignon et al., 2011, 2012; Piitulainen et al., 2013a, 2013b). These results indicate that the PAM stimulator can be used in functional mapping of the SM1 cortex, either alone or as part of a multimodal functional mapping scheme including several functional indicators (Bourguignon et al., 2013).

Table 3

The mean \pm SD goodness-of-fit (GoF) values and 95%-confidence volumes (CVs) of the sources using 4-min, 2-min, and 1-min analysis duration in the right-index finger movements at 3, 6 and 12 Hz.

Duration	Right hand 3 Hz		Right hand 6 Hz		Right hand 12 Hz	
	GoF (%)	CV (mm ³)	GoF (%)	CV (mm ³)	GoF (%)	CV (mm ³)
4 min	95.4 \pm 3.3	29 \pm 27	95.5 \pm 2.0	17 \pm 23	95.4 \pm 1.9	106 \pm 122
2 min	95.0 \pm 2.3	51 \pm 58	95.1 \pm 2.4	33 \pm 28	95.2 \pm 3.0	64 \pm 65
1 min	93.5 \pm 3.7	66 \pm 58	94.6 \pm 2.9	35 \pm 35	93.2 \pm 4.1	128 \pm 194

Recording duration and movement frequency

Stimulation at 3 and 6 Hz elicited transient responses, with the main peak about 85 ms after the movement onset. At 12-Hz movements, the responses transformed into typical steady-state responses where the most prominent frequency, however, was double the movement frequency. The two cycles observed were distinguishable in amplitude and may reflect the alternating activation of the proprioceptors in the flexion and extension phases of the movement.

The signal-to-noise ratio of the responses was so good that only 1-min stimulation of the right-index finger was sufficient to elicit reliable CKC and adequate source modeling at all movement frequencies (3, 6, and 12 Hz). For clinical purposes, ~3-Hz movements for ~2 min thus seem to provide sufficiently robust identification of the SM1 cortex.

Conclusions

Our results imply that the introduced new PAM stimulator for generation of passive finger and toe movements can be efficiently used to quantify the proprioceptive afference to the cortex and to locate the SM1 cortex without concomitant magnetic artifacts. The kinematics during the stimulation proved to be stable, so that the movements were initiated with millisecond accuracy. The here-described PAM stimulator has potential to be used in the research of the sensorimotor system in both healthy subjects and various patient groups.

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